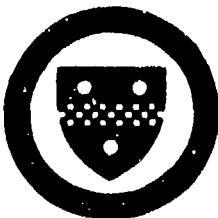


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EDUCATION AND THINKING: THE ROLE OF KNOWLEDGE

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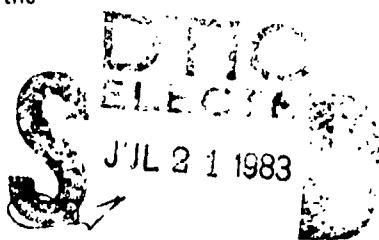
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Abstract

Psychological science is obtaining increased understanding of the nature of human thinking and problem solving. This report addresses the question of how this understanding contributes to instructional practices that might foster these higher order abilities. A brief discussion of the implications of past theories for the teaching of thinking introduces a description of a sample of current programs for improving reasoning and problem-solving skills and related learning abilities. These efforts are then considered in the light of current theory and findings in cognitive science, developmental psychology, and the study of human intelligence. The interaction between the development of problem-solving and learning skills and the acquisition of structures of domain-specific knowledge is discussed. Suggestions are made for developing thinking abilities in the context of the acquisition of knowledge and skill.

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Education and Thinking: The Role of Knowledge*

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The ability of people to reason, understand, solve problems, and to learn on the basis of these cognitive activities is a significant part of current investigation in cognitive psychology. The knowledge that is accumulating should have lasting effects on improving and increasing the general use of these abilities. However, at the present time, the evidence available indicates an apparently improved capability of our schools to teach knowledge of the "basics" without encouraging thinking and mindfulness. This paper is an attempt to consider the scientific background of this dilemma. My plan here is to look at the theories that have encouraged this state of affairs and some of our attempts to cope with it. I will briefly indicate how various psychological theories have influenced the teaching of thinking, in turn: early associationistic theory of learning, notions of Gestalt theory and early work on problem solving, the pioneering work in modern cognitive psychology on information-processing models of problem solving, and more recent work that considers the interaction of acquired knowledge and cognitive process. I hope to show that abilities to think and reason will be attained when these cognitive activities are taught not as subsequent add-ons to what we have learned, but rather, are explicitly

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developed in the process of acquiring the knowledge and skills that we consider the objectives of education and training.

Background

Connectionism. Early in this century, uneasiness with the failure to address the thinking and reasoning potential of human beings was evident in the reaction to E. L. Thorndike's work. He faced the charge that his psychology was mechanistic and explained adequately only the most rote kinds of learning. The appeal of his work, nonetheless, was strong to a generation of educators eager for pedagogical theory. His system was scientific and quantitative, buttressed with enormous quantities of data, and was down to earth in terms of its direct extrapolations to the everyday problems of education (McDonald, 1964).

Thorndike, as a theorist, did not ignore higher level processes, but he reduced them to connectionistic conceptions. His studies fostered the development of curricula that emphasized the specificity of learning and direct experience with the skills and knowledge to be learned, because he had concluded that transfer effects were minimal. His ideas on the specificity of learning supported forms of instruction that many feared failed to encourage the development of higher levels of thinking. Through Thorndike's contributions, psychology was assisted in becoming scientific, but was separated from certain larger issues.

In contrast, John Dewey's less empirical and more philosophical approach attempted to maintain the focus on mental process. His attack on the reflex arc was significant in this regard (Dewey, 1896). The central psychological events of significance in learning and performance were "mediated experiences" and events in relation to their adaptive function. Dewey spoke of learning in terms of aims, purposes and goals,

and problem solving or intelligent action. But this was not a scientific psychology.

Despite the dominance of connectionism, interest in establishing a sound basis for a pedagogy that fosters thinking and reasoning in school learning has been continuously expressed by educators and researchers at least since John Dewey. Let me mention a few outstanding contributions that seem fresh today.

Understanding and cognitive structure. In elementary arithmetic, Thorndike's focus on collecting and strengthening S-R bonds promoted drill methods that were strongly opposed by certain educational psychologists of the time--William Brownell, in particular (cf. Resnick & Ford, 1981). Brownell's studies (1928, 1935), around the 1930's, suggested that drill made children faster and better at "immature" and cumbersome procedures, but failed to develop the kinds of competence that could evolve from an understanding of number concepts. To Brownell, learning arithmetic meant manipulating an integrated set of principles and patterns, and that required more meaningful instruction.

In 1940, George Katona, in his book Organizing and Memorizing (1967, reprinted edition) also emphasized the distinction between "senseless" and "meaningful" learning. Katona's thesis was that the prototype of learning is not associationistic connection, as Thorndike advocated, but rather, the development of cognitive organization. Organizational structures enable the acquisition and preservation of facts, and the command of a large amount of specific information derives from this organization. Mechanical memorization is a limiting case that is resorted to only when a lack of inherent relations in the material being learned excludes the possibility of understanding.

Also, in 1945, Max Wertheimer, in his book on Productive Thinking (1959, enlarged edition), described an insightful series of studies on problem solving in mathematics and science. His discussion of solving for the area of a parallelogram, in which he analyzed the structural understanding that could facilitate transfer to new problems, is widely cited even today. Thus, in the 1930's and 1940's, the polarities of drill and practice on the one hand, and the development of understanding on the other were apparent--and this dichotomy still challenges theory and practice today.

In the late 1950's and early 60's, behavioristic psychology and its expression in programmed instruction strongly influenced instructional theory. Modern theories that are now contributing to the teaching of reasoning and understanding were beginning to emerge. This transition can be expressed here by personal anecdote through the contrast between my own work and the ideas of Bruner. In my writing at that time, I described the design of programmed-instruction lessons, based upon the principles of Skinner's operant analysis (Taber, Glaser, & Schaefer, 1965). Bruner (1964) also described elements of instruction. He talked about the sequence of instruction, the form of pacing, reinforcement and feedback as I did. However, in contrast to my description, he also talked about the structure and form of knowledge, the representation of knowledge, and the influence of representation on the economy and generative power of acquired performance. This personal experience, on a small scale, mirrored for me the changes in psychological theory that were occurring.

The persistence of older influences. Still, the utilization of older theories was widespread, and their impact and limitations are manifest today. In teaching reading, attention has been devoted to the acquisition of basic skills such as sound-symbol correspondence, decoding from print to sound, and phoneme and word recognition. The contributions of code and language approaches to instruction in beginning reading skills have been increasingly understood and have contributed significantly to the design of instructional materials and procedures. However, long-term effects of well-constructed primary curricula do not necessarily show up in the later acquisition of inferential and critical thinking skills required to comprehend text with meaning and understanding (National Assessment of Educational Progress, 1981; Resnick, 1979). Studies on the outcomes of schooling show that while elementary skills are improving, higher level processes are being acquired less well.

In mathematics, there appears to be an increase in the performances associated with basic skill and computation, but little improvement and even a reported decline in mathematical understanding and problem solving (National Assessment of Educational Progress, 1981). The evidence is reiterated in science education. In a long-range perspective of various issues in this field, Champagne and Klopfer (1977) point out that despite the continuing philosophical commitment of science educators to scientific thinking, little of current practice adequately reflects this philosophy. Although there has been much work on defining objectives of science instruction that specify problem-solving criteria, instruction that fosters, and tests that assess, problem-solving ability are far from satisfactory.

Some Curricula for Reasoning, Problem Solving, and Learning Skills

To this point, I have described past aspirations and current shortcomings. Over the past 10 to 15 years, however, certain school programs and textbooks have been designed to encourage thinking, problem solving, and abilities for learning (see Chipman, Segal, & Glaser, in press; Segal, Chipman, & Glaser, in press; and Tuma & Reif, 1980 for a discussion of these attempts). As I view these programs, they can be categorized as follows: (a) process-oriented programs, (b) programs that use generally familiar knowledge, (c) problem-solving heuristics in well-structured domains, and (d) logical thinking in the context of the acquisition of basic skills.

Process-oriented programs. The goal of the first two programs I mention is to develop habits of reasoning and skills of learning to improve performance of a general metacognitive, self-monitoring character. It has previously been assumed that good problem solvers show more conscious awareness and use of active self-monitoring procedures than is apparent in the passive performance of poor problem solvers (Bloom & Broder, 1950). One example of a program designed to counteract this problem was developed by Whimbey and Lochhead (1980) entitled, "Problem Solving and Comprehension: A Short Course in Analytical Reasoning." The program requires thinking aloud to a partner about the steps taken in solving problems, problems like those used on intelligence, aptitude, and simple achievement tests. The partner points out but does not correct errors. The program assumes that few errors are made because of lack of knowledge of vocabulary, arithmetic facts, etc., but rather because of errors in reasoning such as: failing to observe and use all relevant facts of a problem; failing to approach

the problem in a systematic, step-by-step manner; jumping to conclusions and not checking them; and failing to construct a representation of the problem. Through carefully designed problem exercises, the program elicits procedures for reasoning and problem solving that avoid them.

A second example is the longer term program developed by Feuerstein, Rand, Hoffman, and Miller (1980) entitled, "Instrumental Enrichment: An Intervention Program for Cognitive Modifiability." Similar to the preceding program, the authors of this program attribute poor performance to general cognitive deficiencies that result in unsystematic information intake, impaired planning behavior, inability to define problem goals, impulsive acting out, trial and error behavior, and lack of appropriate cue discrimination and generalization. The instrumental enrichment program combines a wide variety of progressively demanding exercises with a set of didactic techniques that provide systematically ordered and intentionally scheduled opportunities for reasoning and problem solving. The tasks used in the program are to some extent like psychometric and psychological laboratory tasks. Sets of such tasks comprise units which encourage cognitive activities like perceptual organization, problem representation, planning, goal analysis, and problem restructuring. This program, like Whimbey and Lochhead's, is seen as a bridge between relatively content-free exercises and thinking in curriculum content domains.

Programs that use generally familiar knowledge. The next two programs I describe differ from those just mentioned in that they teach thinking in the context of generally familiar knowledge. Covington, Crutchfield, Davies, and Olton (1974), have published a program

entitled, "The Productive Thinking Program: A Course in Learning to Think." Each lesson in the program is based on an illustrated story which presents a challenging problem (such as planning a redevelopment project for a city) that the students attempt to solve. The student is led through a problem-solving process, and at appropriate points is required to state the problem in his own words, formulate questions, analyze information, generate new ideas, test hypotheses, and evaluate possible courses of action. These procedures are formulated as thinking guides that are presented throughout the various lessons and problem sets.

Another program developed over the past 10 or so years is The CoRT Thinking Program by de Bono (in press) in England (CoRT stands for Cognitive Research Trust). The specific thinking strategies taught are like the metacognitive, self-monitoring strategies that have been already mentioned. There are a number of features of the program that make it both similar and dissimilar to the others described here. The contents of the program are topics of interest in everyday life, such as deciding upon a career, how to spend one's holiday, moving to a new house, and changing to a new job. This program emphasizes skills that are not dependent on the prior acquisition of curriculum subject matter. However, unlike Whimbey and Lochhead and Feuerstein, The CoRT Program keeps away from puzzles, games, and other such abstractions.

Problem-solving heuristics in well-structured domains. Another category of programs is concerned with teaching skill in problem solving, particularly in formal, well-structured domains like mathematics, physics, and engineering. The mathematician, George Polya (1957) and Newell and Simon (1972) are the guiding spirits. Polya

recommends that explicit attention be paid to heuristic processes as well as to content. He suggests a variety of helpful ideas such as looking for analogical situations; looking for solutions to partial auxiliary problems; decomposing a problem and recombining elements; checking whether the conditions presented in a problem are sufficient, redundant, or contradictory; and working backwards from a proposed solution. He also discusses more specific procedures in mathematical problem solving such as using indirect proofs and mathematical induction. A related program is a course developed by Rubenstein (1975) called, "Patterns of Problem Solving." The instructional tactic of the book, in general, is to introduce the student to a wide range of specific problem-solving techniques that can be brought to bear on problems they encounter in their various specializations.

A similar, but somewhat different approach, is a book by Wickelgren (1974) entitled, "How to Solve Problems: Elements of a Theory of Problems and Problem Solving." This text is explicitly designed to improve the reader's ability to solve mathematical, scientific, and engineering problems. His assumption is that general problem-solving methods can be of substantial help to the students in learning more specialized methods in a subject-matter field, and in working problems where they do not completely understand the relevant material or the particular class of problems involved. Another program in this genre is a recent book by Hayes (1981), entitled "The Complete Problem Solver," used to teach a college course on general problem-solving skills. This program is designed to introduce skills that improve problem solving, and at the same time, provide up-to-date information about the psychology of problem solving.

Logical thinking in the context of the acquisition of basic skills.

Finally, I turn to a program that aims at fostering thinking skills in the specific context of school curricula, a contrast to the previous relatively curriculum-unencumbered programs that I have described. A program by Lipman, Sharp, and Oscanyan (1979, 1980) entitled, "Philosophy for Children" attempts to do this. Their contention is that the hierarchy of basic skills to complex processes from, for example, decoding in reading to meaningful comprehension, is so ingrained in educational philosophy and in educational research that it is difficult to conceive of the interdependence of basic skills and the skills of reasoning and thinking. While it is believed that thinking skills are complex and basic skills more rudimentary, just the reverse may be the case. A discipline which stresses formal inquiry might be considered in the very beginning of a curriculum rather than later in the educational process. Toward this end the several parts of this program employ the procedures of philosophic logic and inquiry in the context of science, ethics, social studies, and language arts. The program designers believe that thinking is deemphasized in education that gives either knowledge acquisition or problem-solving techniques a primary status. The pragmatic nature of inquiry, Lipman states, must be made apparent, in the course of acquiring knowledge and skill.

Comment

The above descriptions report current practices that are evident in published programs and texts used in various educational settings. With some exceptions, I find that most of these programs place emphasis on the teaching of general processes--general heuristics and rules for reasoning and problem solving--that might be acquired as transferable habits of thinking. Also, in large part, abstract tasks, puzzle-like

problems, and informal life situations are used as content. An avoidance of the complexity of subject-matter information is typical. The practical reason offered is that teachers and students would find this difficult to manage and inhibiting of the thinking processes that need to be practiced and acquired. The significant aspect is that little direct connection is made with thinking and problem solving in the course of learning cumulative domains of knowledge--that is, in the context of acquiring structures of knowledge and skill that comprise the subject matter of schooling.

The deep, underlying reason for this, I believe, is a matter of theory and knowledge of human thinking. The programs that I have described are based on early theories of human cognition--some that stem from psychometric notions of inductive reasoning, and from concepts of divergent thinking in older theories of problem solving. Others derive from early information-processing theory that explored knowledge-lean problems, and that concentrated on basic information-processing capabilities that humans employ when they behave more or less intelligently in situations where they lack any specialized knowledge and skill. When faced with such novel situations, they resort to general methods. But, in the context of acquired knowledge and specific task structures, these methods may be less powerful; they lack the focus of domain specificity because of their wide applicability and generality (Newell, 1980). While the general heuristic processes that humans use to solve problems have been richly described by the pioneering work of Newell and Simon (1972) and others (e.g., Greeno, 1978), this research used relatively knowledge-free problems, and as such, offered limited insight into learning and thinking that requires domain-specific knowledge.

In contrast, more recent work on problem solving which has been done in knowledge-rich domains shows strong interactions between structures of knowledge and cognitive processes. The results of this newer research and theory force us to consider the teaching of thinking not primarily in terms of general processes, but also in terms of knowledge structure-process interactions. The feasibility of a more integrated approach is now increased by studies in developmental psychology and cognitive science in which attention has turned to cognitive process in the context of the acquisition of structures of knowledge and skill.

The Focus on Knowledge

Let me consider now this focus on knowledge. Much recent work emphasizes a new dimension of difference between individuals who display more or less ability in thinking and problem solving. This dimension is the possession and utilization of an organized body of conceptual and procedural knowledge, and a major component of thinking is seen to be the possession of accessible and usable knowledge. Evidence from a variety of sources converge on this conception: data and theory in developmental psychology, studies of expert and novice problem solving, and process analyses of intelligence and aptitude test tasks.

Developmental studies. The interaction of knowledge and cognitive process has been shown in the study of memory. For example, Chi (1978) studied recall with children and adults in the standard memory for digits task and in memory for chess positions comparing high-knowledge 10-year-old children who played tournament chess and low-knowledge adults who knew little chess. In the digit span test, children and adults exhibited the typical result--digit span being lower for children

than adults. In recall for chess positions, however, the children's memory was far superior to the adults, replicating the chess studies of Chase and Simon (1973) in which high-knowledge subjects show better memory and encoding performance than low-knowledge individuals. This superiority is attributed to the influence of knowledge in this content area rather than the exercise of memory strategies as such. The hypothesis is that changes in the knowledge base can produce sophisticated cognitive performance. This relationship is further illustrated in Chi and Koeske's (1983) study of a single child's recall of dinosaur names. Changes in the amount and structure (the relationship between dinosaurs and identifying features) of knowledge influenced the amount of recall, and general memory strategy appeared to play a minimal role.

Next, I cite two sets of developmental studies that suggest that reasoning and problem solving are greatly influenced by experience with new information. In a recent study, Susan Carey (in press) has proposed an interesting interpretation of animistic thinking in young children. Based upon her own observations of a child's concept of "alive," she suggests that a child's confusion about the concept of "being alive" stems, in large part, from impoverished biological knowledge. Young children, 4 to 7 years of age, believe that biological properties such as eating, breathing, sleeping, and the possession of internal organs such as a heart, are primarily properties of people, not necessarily of animals. The more similar an animal is seen to be to a person, the more likely children are to judge that the animal has these attributes. Their knowledge is organized around an undifferentiated people structure so that they are as likely to say worms have bones as to say that worms eat. By age 10, this has all changed. Fundamental biological functions

such as eating and breathing are attributed to all animals and are differentiated from properties such as having bones. Humans become one species of mammal among many, each with basic similarities and differences. This change reflects, according to Carey, a reorganization of knowledge brought about by school learning and world knowledge: for 4- to 7-year olds, biological properties are organized in terms of their knowledge of human activities; for 10-year olds, such knowledge is organized in terms of biological functions. Thus, the younger child's little knowledge of biological functions results in the inability to justify the inclusion and exclusion of humans, animals, plants, and inanimate objects to the concept "alive." In older children, the acquisition of domain-specific information results in structured knowledge that is reflected in the ability to think about properties of the concept "animate," and to reason appropriately.

Carey makes the general point that what can be interpreted as an abstract pervasive change in the child's reasoning and learning abilities is a change that is repeated as knowledge is gained in various domains. These changes come about with the acquisition of specific knowledge, and these knowledge structures comprise theories that enable different kinds of thinking. Theory changes of this kind, like those in science, are made as a wider and wider array of phenomena and problem situations must be explained. The acquisition of knowledge in some domains is more broadly applicable than in others. When knowledge structures of wide application like measurement, number concepts, and arithmetic problem-solving schema become available, learning and thinking in a variety of related domains can be influenced.

The acquisition of specific content knowledge as a factor in acquiring increasingly sophisticated problem-solving ability is also apparent in Robert Siegler's "rule assessment" approach to developmental change (Siegler & Klahr, 1982; Siegler & Richards, 1982). In this work, problem representation based upon appropriate information of a specific domain appears to influence task performance in a way that enables changes in inference processes. In a variant of the balance scale task studied by Inhelder and Piaget, Siegler finds that 5-year-olds have difficulty in solving problems because they fail to encode distance information; they concentrate solely on weight. After training in encoding distance so that it is a salient cue, children use this information to solve problems that involve a more sophisticated theory about the relationship of weight and distance in balance scale problems. Siegler's investigation required a detailed task analysis of the rule and cue knowledge required for different levels of performance. With this information, it was possible to determine the theory that guided a child's performance. Knowing what knowledge a child applied to a problem enabled the experimenter to match the child's current state of knowledge to learning events that helped the child to move to a new level of reasoning. With increasing knowledge, children could exercise complex rules that applied to a larger set of problems.

The significance of these data for our concern with the development and teaching of reasoning is that thinking is greatly influenced by experience with new information. Change occurs when theories are confronted by specific challenges and contradictions to an individual's knowledge. Siegler and Richards (1982) state the issue clearly:

Developmental psychologists until recently devoted almost no attention to changes in children's knowledge of specific

content. . . . Recently, however, researchers have suggested that knowledge of specific content domains is a crucial dimension of development in its own right and that changes in such knowledge may underlie other changes previously attributed to the growth of capabilities and strategies. (p. 930)

Problem solving in experts and novices. The focus on knowledge is further evidenced in recent research on expert problem solving (Chase & Simon, 1973; Chi, Glaser, & Rees, 1982; Larkin, McDermott, Simon, & Simon, 1980; Lesgold, Feltovich, Glaser, & Wang, 1981; Voss, Greene, Post, & Penner, in press). Current studies of high levels of competence support the recommendation that an important focus for understanding expert thinking and problem solving is investigation of the characteristics and influence of organized knowledge structures acquired over long periods of learning and experience. In this endeavor, work in artificial intelligence has made significant contributions; in contrast to an earlier emphasis on "pure" problem-solving techniques to guide a search for any problem (Newell, Shaw, & Simon, 1960), this field, too, has come to focus on the structure of domain-specific knowledge. This shift in AI is characterized by Minsky and Papert (1974) as a change from what they call a power-based strategy for achieving intelligent thinking to a knowledge-base emphasis. They write as follows:

The Power strategy seeks a generalized increase in computational power. It may look toward new kinds of computers . . . or it may look toward extensions of deductive generality, or information retrieval, or search algorithms. . . . In each case the improvement sought is . . . independent of the particular data base.

The Knowledge strategy sees progress as coming from better ways to express, recognize, and use diverse and particular forms of knowledge. . . . it is by no means obvious that very smart people are that way directly because of the superior power of their general methods--as compared with average people. . . . A very intelligent person might be that way because of specific local features of his knowledge-organizing knowledge rather than because of global qualities of his "thinking" . . . (p. 59)

Stimulated by this trend, Chi, Lesgold, and I have undertaken investigations to construct a theory of expert problem solving and its acquisition based upon empirical descriptions of expert and novice performance in complex knowledge domains. The knowledge domains we study are physics, particularly mechanics (Chi, Glaser, & Rees, 1982) and radiology, particularly the interpretation of x-rays (Lesgold et al., 1981). A guiding question for us in this work is: How does the organization of the knowledge base contribute to the observed thinking of experts and novices? Our assumption is that the relation between the structure of the knowledge base and problem-solving process is mediated through the quality of the representation of the problem. We define a problem representation as a cognitive structure corresponding to a problem that is constructed by a solver on the basis of domain-related knowledge and its organization. At the initial stage of problem analysis, the problem solver attempts to "understand" the problem by constructing an initial problem representation. The quality, completeness, and coherence of this internal representation determines the efficiency and accuracy of further thinking. And these characteristics of the problem representation are determined by the

knowledge available to the problem solver and the way the knowledge is organized.

Our research suggests that the knowledge of novices is organized around the literal objects explicitly given in a problem statement. Experts' knowledge, on the other hand, is organized around principles and abstractions that subsume these objects. These principles are not apparent in the problem statement but derive from knowledge of the subject matter. In addition, the knowledge of experts includes knowledge about the application of what they know. These aspects of knowledge comprise tightly connected schema for the expert. The novice's schema, on the other hand, may contain sufficient information about a problem situation, but lack knowledge of related principles and their application. Our interpretation is that the problem-solving difficulty of novices can be attributed, to a large extent, to the inadequacies of their knowledge bases, and not to limitations in their processing capabilities such as the inability to use problem-solving heuristics. Novices show effective heuristics; however, the limitations of their thinking derive from their inability to infer further knowledge from the literal cues in the problem statement. In contrast, these inferences are necessarily generated in the context of the knowledge structure that the experts have acquired.

These results must be considered in the light of the work that followed the theoretical contribution of Newell and Simon. Problem-solving research proceeded to model search behavior, and to verify that humans indeed solve problems according to basic heuristic processes such as means-end analysis. Numerous puzzle-like problems were investigated, all of which indicated that humans do solve problems

according to this theoretical analysis to some degree (Greeno, 1978). However, the study of problem solving with large knowledge bases has provided a glimpse of the power of human thinking to use a large knowledge system in an efficient and automatic manner--in ways that minimize search. Current studies of high levels of competence support the recommendation that a significant focus for understanding expert thinking and problem solving and its development is investigation of the characteristics and influence of organized knowledge structures that are acquired over long periods of time.

Process analysis of aptitude and intelligence. I consider now the third converging area--process analysis of aptitude and intelligence. In recent years, there has been extensive theoretical and empirical investigation of information-processing approaches to the study of intelligence and aptitude (cf. Sternberg, 1977, 1981b; Hunt, Frost, & Lunneborg, 1973). Reflections on this work are relevant to our concerns here. In my own research with Pellegrino and our associates on models of aptitude test performance (Pellegrino & Glaser, 1982), we have found that several interrelated components of performance differentiate high- and low-scoring individuals. One component is reflected in the speed of performance and appears to involve the management of working memory processes. A second component is conceptual knowledge of item content; low-scoring individuals with less available knowledge encode at surface feature levels, rather than at levels of generalizable concepts, which limits their inferential ability. A third component is knowledge of the solution procedures required for solving a particular task form, such as analogical reasoning. Low-scoring individuals display a weak knowledge of procedural constraints which result in procedural bugs and the inability to recover higher level problem goals when subgoals need to be

pursued.

We have speculated on the implications of these results for fostering the development of aptitudes for learning. The memory management component suggests the possibility of influencing processing skills--such as by training better methods for organizing and searching memory as suggested in a number of the existing programs reviewed earlier. The other two components, however, concerned with conceptual and procedural knowledge, suggest a different emphasis. In contrast to process training, training related to an individual's knowledge base would involve acquiring and using conceptual information and knowledge of problem-solving constraints. In our studies, high-aptitude individuals appear to be skillful reasoners because of the level of their content knowledge and because of their knowledge of the procedural constraints of a particular problem form such as inductive or analogical reasoning. This observation leads to the suggestion that improvement in the skills of learning, such as required on aptitude and intelligence tests, takes place through the exercise of conceptual and procedural knowledge in the context of specific knowledge domains. Learning and reasoning skills develop not as abstract mechanism of heuristic search and memory processing. Rather, they develop as the content and concepts of a knowledge domain are attained in learning situations that constrain this knowledge to serve certain purposes and goals. Effective thinking is the result of proceduralized knowledge--knowledge that becomes associated with the conditions and constraints of its use. As this knowledge is used and transferred to domains of related knowledge, the skills involved probably then become more generalizable so that intelligent performance is displayed in the context of novel ("nonentrenched") situations (Sternberg, 1981a).

Schemata and Pedagogical Theories

This discussion on the significance of organized knowledge can be pulled together by introducing the theoretical concept of prototypical knowledge structures or schemata. Cognitive psychologists in accounting for various phenomena in memory, comprehension, problem solving, and understanding have found it useful to appeal to the notion of schemata. Schema theory attempts to describe how acquired knowledge is organized and represented and how such cognitive structures facilitate the use of knowledge in particular ways.

A schema is conceived of as a modifiable information structure that represents generic concepts stored in memory. Schemata represent knowledge that we experience--interrelationships between objects, situations, events, and sequences of events that normally occur. In this sense, schemata are prototypes in memory of frequently experienced situations that individuals use to interpret instances of related knowledge (Rumelhart, 1981). People typically try to integrate new information with prior knowledge, and in many situations, where they cope with new information, much is left out so that they could never understand the situation without filling it in by means of prior knowledge. Estes (National Academy of Sciences, 1981) explains this point by describing the following vignette: "At the security gate, the airline passenger presented his briefcase. It contained metallic objects. His departure was delayed." In order to understand this commonplace incident, an individual must have a good deal of prior knowledge of air terminals. This kind of prior knowledge is represented in memory by a schema that specifies the relationship between the roles played by various people in the terminal, the objects typically

encountered, and the actions that typically ensue. Schema theory assumes that there are schemata for recurrent situations that are experienced, and a major function of schemata is the construction of an interpretation of a situation.

A schema can be thought of as a theory or internal model which is used and tested as individuals instantiate the situations they face. As is the case for a scientific theory, a schema is compared with observations and, if it fails to account for some aspects, the schema can be accepted, rejected, modified, or replaced. Like a theory, a schema is a source of prediction of events and enables individuals to make assumptions about events that generally occur in a particular situation--so that the knowledge they infer goes beyond the observations that are available in any one instance. Such prototypical structures play a central role in thinking and understanding, and the reasoning that occurs takes place in the context of these specific networks of knowledge.

Knowledge of the prototypical structures that describe problem situations are often forms of tacit knowledge present in effective problem solvers and skilled learners. Such available knowledge has been made apparent in research on children's ability to solve word problems in arithmetic. Different kinds of word problems vary in the semantic relationship that exists between quantities, and children differ in their knowledge of these categories of relations, i.e., knowledge about increases, decreases, combinations, and comparisons involving the sets of objects in a problem. Riley, Greeno and Heller (1983) have explicitly described categories of conceptual knowledge of problem structures that influence problem solving and learning. "Change" and

"equalizing" categories describe addition and subtraction as actions that cause increases or decreases in some quantity. "Combine" and "compare" problem categories involve static relationships between quantities. For example, in change problems the initial quantity of Joe's three marbles is increased by the action of Tom giving Joe five more marbles. Equalizing problems involve two separate quantities, one of which is changed to the same as the other quantity; the problem solver is asked to change the amount of Joe's marbles to the same as the amount of Tom's marbles. In combine problems there are two distinct quantities that do not change; Joe has three marbles and Tom has five marbles and the problem solver is asked to consider them in combination: "How many marbles do Joe and Tom have altogether?" Typical compare problems also describe two static quantities, but the problem solver is asked to determine the difference between them: "How many marbles does Joe have more than Tom?"

The influence of children's knowledge of these problem structures on problem solution is evident in studies showing that different problem categories are not equally difficult even when they require the same operations for solution. This suggests that solving a word problem requires more knowledge than just knowing the operations and having some skill in applying them. Studies also show that young children can solve some word problems even before they have received any instruction in the syntax of arithmetic; and even after studying the formal notation, they may not translate simple word problems into equations. These studies suggest that children, in large part, base solutions on their knowledge and understanding of the prototypical semantic structure in a problem situation. Riley, Greeno, and Heller present analyses of children's problem-solving skill in which the major influence appears to be the

acquisition of knowledge structures which enable improved ability to represent problem information. They also propose that knowledge of problem schemata is related to acquisition of efficient counting procedures and to more sophisticated problem-solving procedures. The strong assumption, then, is that problem solving, comprehension, and learning are based on knowledge, and that people continually try to understand and think about the new in terms of what they know. If this is, indeed, the case, then it seems best to teach such skills as solving problems and correcting errors of understanding in terms of knowledge domains with which individuals are familiar. Abilities to make inferences and to generate new information can be fostered by insuring maximum contact with prior knowledge that can be restructured and further developed (Norman, Gentner, & Stevens, 1976). The notion of schemata as theories that are a basis for learning suggests several important pedagogical principles. First, one must understand an individual's current state of knowledge in a domain related to the subject matter to be learned, and within which thinking skills are to be exercised. Second, a "pedagogical theory" can be specified by the teacher that is different from, but close to, the theory held by the learner. Then third, in the context of this pedagogical theory, a student can test, evaluate, and modify his current theory so that some resolution is arrived at between the two. Thus, the stage is set for further progression of schemata changes as the student works with, debugs, and generates new theories.

When schema knowledge is viewed as a set of theories, it becomes a prime target for instruction. We can view a schema as a pedagogical mental structure, one that enables learning by facilitating memory retrieval and the learner's capacity to make inferences on the basis of current knowledge. When dealing with individuals who lack adequate knowledge organization, we must provide a beginning knowledge structure. This might be accomplished either by providing overt organizational schemes or by teaching temporary models as scaffolds for new information. These temporary models, or pedagogical theories as I have called them, are regularly devised by ingenious teachers. Such structures, when they are interrogated, instantiated, or falsified, help organize new knowledge, and offer a basis for problem solving that leads to the formation of more complete and expert schemata. The process of knowledge acquisition can be seen as the successive development of structures which are tested and modified or replaced in ways that facilitate learning and thinking.

Along these lines, the work of diSessa in his studies of learning physics is to be noted (1982). diSessa has conceived of the notion of "genetic task analysis." As I understand this notion, it is different from the usual forms of task analysis in the sense that it attempts to identify components of pre-existing theories of knowledge which can be involved in the development of more sophisticated theories--like, in learning elementary physics, the transition of naive Aristotelian theory to Newtonian interpretations. What is important to analyze is not the logical prerequisites such as identified in a Gagne hierarchy, but rather "genetically antecedent partial understandings" (p. 63). These understandings are genetic in the sense that they are "pedagogical theories" which can be thought about and debugged in the course of the

development of further understanding.

Interrogation and confrontation. The pedagogical implication that follows from this is that an effective strategy for instruction involves a kind of interrogation and confrontation. Expert teachers do this effectively, employing case method approaches, discovery methods, and various forms of Socratic inquiry dialogue. Methods of inquiry instruction have been analyzed by Collins and Stevens (1982), and their findings suggest a useful approach to the design of tutorial instructional systems. A major goal of good inquiry teachers, in addition to teaching facts and concepts about a domain, is to teach a particular rule or theory for the domain. This is done, in part, by helping the learner make predictions from and debug his current theory. A second goal is to teach ways to derive a rule or theory for related knowledge. The student learns what questions to ask to construct a theory, how to test one, and what its properties are. From their protocols of effective teachers, Collins and Stevens prepared a detailed account of recurring strategies that teachers used for selecting cases and asking questions that confront the student with counterexamples, possibilities for correct and incorrect generalization, and other ways of applying and testing their knowledge.

Such interactive inquiry methods are powerful tools for teaching thinking in the context of subject matter. Certainly, inquiry methods are tuned to the teaching of theories; they encourage conceptual understanding, involve and therefore motivate students, and can be adapted to the needs of different students. Used with inadequate skill, however, as Collins and Stevens point out, an inquiry approach can become an inquisition that leaves many students behind, in dread of

having their ignorance exposed. The method requires that a teacher be continually vigilant, and keep in mind the particulars of each student's thinking.

Current approaches to inquiry teaching and theory-targeted instruction are of interest. Recent research has emphasized that people's everyday understanding of physics is closer to the physics of Aristotle than to that of Newton. Even after a physics course, many people hold to a naive, pre-Newtonian view of basic mechanics (Champagne, Klopfer, & Anderson, 1980; McCloskey, Caramazza, & Green, 1980). To deal with this problem, several projects have been undertaken to provide microworlds simulated on a computer in which students can explore the implications of their beliefs (cf. Papert, 1980). Excellent examples have been created by diSessa (1982) and by Champagne, Klopfer, Fox, and Scheuerman, (1982), who have designed computer simulations of classic physics experiments which allow students to reason about implications of their own theories and then compare events in their world to the predictions of other theories.

General and Specific Thinking Skills

Now that I have emphasized teaching thinking in the context of knowledge structures and the acquisition of new knowledge, I must return to the development of general intellectual capabilities somewhat like those that are the objectives of instruction in the school programs that I mentioned. In what follows, I would like to refer particularly to the self-regulatory or metacognitive capabilities present in mature learners. These abilities include: knowing what one knows or does not know, predicting the outcome of one's performance, planning ahead, efficiently apportioning one's time and cognitive resources, and

monitoring and editing one's efforts to solve a problem or to learn (Brown, 1978). These skills vary widely in people. Although individuals can be taught knowledge of a rule, a theory or a procedure, if transfer of learning to new situations is a criterion, then they need to know how to monitor the use of this knowledge. Self-regulatory activities thus become important candidates for instruction, and their presence can predict student ability to solve problems and learn successfully. My hypothesis is that these self-monitoring skills can become abstracted competencies when individuals use them in a variety of literacy skills and specific fields of knowledge. They are learned as generalizations of the cognitive processes employed in daily experiences with the details of attained and new knowledge. However, these general methods may be a small part of intelligent performance in specific knowledge domains where one can rapidly access learned schemata and procedures to manipulate a problem situation. General processes may be more largely involved when an individual is confronted with problems in unfamiliar domains.

The current literature poses a dilemma between instructional emphasis on general domain-independent skills or domain-specific skills (Chipman, Segal, & Glaser, in press; Segal, Chipman, & Glaser, in press; Tuma & Reif, 1980). It is evidenced by the emphasis of most of the school programs I described on domain-free methods, and by current research on problem solving in the context of specific knowledge structures. A central issue for theory and experiment in resolving this issue will focus on the transferability of acquired knowledge and skill. There are several possibilities. First, if we believe that broad domain-independent knowledge and skill about thinking and problem solving is teachable in a way that enables this information to be

generally usable in a variety of situations, then we can adopt the tactics of general methods programs. Second, on the other hand, if we believe that humans, for the most part, show limited capability in transferring such general skills and if knowledge structure-process interactions are powerful aspects of human performance, then training in the context of specific domains is called for. Along the general-specific dimension of these two approaches, the dilemma posed is that general methods are weak because they are applicable to almost any situation, and will not alone provide an evaluation of specific task features that enable a problem to be solved. In contrast, skills learned in specific contexts are powerful enough when they are accessed as part of a knowledge schema, but the problem of general transfer remains.

A third possibility is that both levels of thinking can be taught as subject-matter knowledge and skill is acquired. Specific declarative knowledge and associated procedural knowledge would be learned, as well as general processes involved in using one's knowledge and skill. Recent research of this kind has been reported by Brown (in press), and she suggests a combined approach. In carrying out instruction, a student's strengths and weaknesses in learning in a particular domain could be assessed. If a student has acquired much of the specific knowledge needed for subject-matter mastery, instruction aimed primarily at general self-regulatory skills might be indicated. However, if a student shows competence in general problem-solving and self-regulatory strategies, and is likely to employ them to guide learning in a new area, then an emphasis on knowledge and skill specific to a domain is called for. The relative emphasis on general and specific knowledge in instruction will vary as a function of both the competence of the

learner and the characteristics of the domain being taught. This tactic seems to be a reasonable one to investigate, but rather than switching between general and specific, I would also examine a fourth possibility, i.e., teaching specific knowledge domains in interactive, interrogative ways so that general self-regulatory skills are exercised in the course of acquiring domain-related knowledge.

Conclusion

Psychological knowledge has developed cumulatively through S-R formulations, Gestalt concepts, information-processing models, and current knowledge-based conceptions. With our modern knowledge, current research and development is increasing the likelihood that we can move to a new level of application--where a wide spectrum of thinking skills is sharpened in the course of education and training. Few other educational possibilities beckon us to apply our energies and exploratory talents as much as this one. Teaching thinking has been a long-term aspiration, and now progress has occurred that brings it into reach. The cognitive skills developed by people in a society are profoundly influenced by the ways in which knowledge and literacy are taught and used. We should take heed. The task is to produce a changed environment for learning--an environment in which there is a new relationship between students and their subject matter--an environment where knowledge and skill become objects of interrogation, inquiry, and extrapolation. As individuals acquire knowledge, they also should be empowered to think and reason.

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